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Evidence for Core Collapse in the Type Ib/c SN 1999ex

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Abstract. We present optical and infrared spectra of SN 1999ex, which are characterized by the lack of strong hydrogen lines, weak optical He I lines, and strong He I λ10830,20581. SN 1999ex provides a clear example of an intermediate case between pure Ib and Ic supernovae, which suggests a continuous spectroscopic sequence between SNe Ic to SNe Ib. Our $UBVRIz$ photometric observations of SN 1999ex started only one day after explosion, which permitted us to witness an elusive transient cooling phase that lasted 4 days. The initial cooling and subsequent heating due to ^{56}Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe produced a dip in the lightcurve which is consistent with explosion models involving core collapse of evolved massive helium stars, and not consistent with lightcurves resulting from the thermonuclear runaway of compact white dwarfs.

1 Introduction

In a rare occurrence the spiral galaxy IC 5179 (cz=3,498 $km\ s^{-1}$) produced two supernovae (SNe) in an interval of only three weeks. The first object (SN 1999ee) was a Type Ia event discovered by us 10 days before maximum [16]. The early discovery motivated us to use the YALO and 0.9-m telescopes at the Cerro Tololo Inter-American Observatory in order to secure nightly $UBVRIz$ photometric observations of this event, and the YALO and Las Campanas 1-m and 2.5-m telescopes to obtain JHK photometry. Although the second object (SN 1999ex) exploded three weeks later and was promptly present in our CCD images we did not notice its presence. Its discovery had to await independent observations obtained at Perth Observatory [14]. Once SN 1999ex was reported to the IAU Circulars we initiated an optical and infrared (IR) spectroscopic followup using the European Southern Observatory NTT and Danish 1.5-m telescope at La Silla, and the VLT at Cerro Paranal. Our spectroscopic and photometric observations of SN 1999ex constitute an unprecedented dataset which provides support to our understanding of the nature of core collapse SNe. In this paper we show some of our observations and their interpretation. For a detailed report of our observations the reader is referred to [8], [23], and [13].

2 Spectroscopic Observations

Fig. 1 compares the near-maximum optical spectra of SN 1999ex to those of the prototype of the Ib class SN 1984L [9], and the Type Ic SNe 1994I [5] and 1987M [4]. The first spectrum of SN 1999ex was characterized by a reddish continuum and several broad absorption/emission features due to Ca II H&K $\lambda\lambda$3934,3968, Na I D $\lambda\lambda$5890,5896, and the Ca triplet with a clear P-Cygni profile. This spectrum bore quite resemblance to that of the Type Ic SN 1994I [5]. However, SN 1999ex showed evidence for He I absorptions (shown with tick marks) of moderate strength in the optical region, thus suggesting the existence of an intermediate Ib/c case. Our observations of SN 1999ex provide a clear link between the Ib and Ic classes and suggest that there is a continuous sequence of SNe Ib and Ic objects.

The presence of helium in the atmosphere of SN 1999ex can be further examined in our IR observations shown in Fig. 2. The strong feature near 1.05 μm probably had a significant contribution from He I λ10830, although it could be blended with lines of C I and Si I [17,1]. If this feature was He I λ10830 it would imply an expansion velocity of 6,000-8,000 km s^{-1}, which matches very well the velocities derived from the Fe and Na lines. This identification is supported by the presence of He I λ20581 with the same expansion velocity deduced from He I λ10830. Our IR spectra of SN 1999ex provide unambiguous proof that helium was present in the atmosphere of this intermediate Ib/c object. A detailed atmosphere model could be very useful at placing specific limits on the helium mass in the ejecta of SN 1999ex and constraining the nature of its progenitor. Evidently, K-band spectroscopy is probably the best tool to explore the presence or absence of helium in the atmospheres of SNe Ib and Ic.

The question of whether or not SNe Ic have helium is still controversial. A detailed inspection of the spectra of SN 1994I led Filippenko et al. [5] to conclude that weak He I lines were probably present in the optical region and that He I λ10830 was very prominent, although its Doppler shift implied an unusually high expansion velocity $\sim$16,600 km s^{-1} as can be seen in the bottom panel of Fig. 1. Clocchiatti et al. [3] confirmed these observations and found evidence that He I λ5876 was also present in SN 1994I with a blueshift of $\sim$17,800 km s^{-1}. They also reported high velocity He I λ5876 in the spectra of the three best-observed Type Ic SNe (1983V, 1987M, and 1988L), which led them to conclude that most, and probably all, SNe Ic have optical He I lines. This conclusion, however, was recently questioned by Millard et al. [17] and Baron et al. [1] by means of spectral synthesis models which showed that the 1.05 μm feature could be accounted with lines of C I and Si I. Moreover, Baron et al. [1] argued that the feature attributed to He I λ5876 in the spectrum of SN 1994I could be a blend of other species. Recently, Matheson et al. [15] compiled and analyzed a large collection of spectra of SNe Ib and Ic and did not find compelling evidence for helium in the spectra of SNe Ic. Evidently, there is no consensus yet about this issue. The existence of an intermediate Ib/c object such as SN 1999ex suggests a continous transition between SNe Ib and SNe Ic so it is likely that some SNe Ic have some helium in their atmospheres.

3 Photometric Observations

Fig. 3 shows the *UBVRIz* lightcurves of SN 1999ex. Clearly the observations began well before maximum light thanks to our continuous followup of IC 5179 owing to the prior discovery of SN 1999ee. The first detection occurred on JD 2,451,481.6 in all filters. Excellent seeing images obtained on the previous night allowed us to place reliable upper limits to the SN brightness, which permitted us to conclude that the explosion took place on JD 2,451,480.5 ($\pm$0.5). Along with the Type Ic hypernova 1998bw [6], these are the earliest observations of a SN Ib/c. The most remarkable feature in this figure is the early dip in the U and B lightcurves – covering the first 4 days of evolution – after which the SN steadily rose to maximum light. Similar initial upturns have been observed before in SN Ic 1998bw [6], SN II 1987A [7], and SN IIb 1993J [20,19]. For these SNe II it is thought that the initial dip corresponded to a phase of adiabatic cooling that ensued the initial UV flash caused by shock emergence which superheated and accelerated the photosphere. The following brightening is attributed to the energy deposited behind the photosphere by the radioactive decay of ^{56}Ni$\rightarrow^{56}$Co$\rightarrow^{56}$Fe. This similarity suggests that the progenitor of SN 1999ex was a massive progenitor that underwent core collapse. Woosley et al. [24] computed Type Ib SN models consisting of the explosion of an evolved 6.2 $M_\odot$ helium star. Their Figure 7 shows the bolometric luminosities of three models with different explosion energies and ^{56}Ni nucleosynthesis, all of which show an initial peak followed by a dip a few days later and the subsequent brightening caused by ^{56}Ni $\rightarrow$ ^{56}Co $\rightarrow$ ^{56}Fe, making them good models for SN 1999ex.

In order to compare the observations with the models we computed a bolometric lightcurve for SN 1999ex by performing blackbody (BB) fits to our *BVI* photometry (Fig. 4) Among the three SN Ib models of Woosley et al., the one with kinetic energy of 2.7$\times$10^{51} ergs and 0.16 $M_\odot$ of ^{56}Ni provides the best match to SN 1999ex. The agreement is remarkable considering that we are not attempting to adjust the parameters. The initial peak and subsequent dip have approximately the right luminosities although the evolution of SN 1999ex was somewhat faster. The following evolution is well described by the model.

The observation of the tail of the shock wave breakout in SN 1999ex and the initial dip in the lightcurve provides us with an insight on the type of progenitor system for SNe Ib/c. Several different models have been proposed as progenitors for this type of SNe. One possibility is an accreting white dwarf which may explode via thermal detonation upon reaching the Chandrasekhar mass [22,2]. These models are expected to produce lightcurves with an initial peak that corresponds to the emergence of the burning front, a fast luminosity drop due to adiabatic expansion, and a subsequent rise caused by radioactive heating. Given the compact nature of the progenitor ($\sim$1,800 km) the cooling time scale by adiabatic expansion is only a few minutes [11] and the lightcurve is entirely governed by radioactive heating [10]. Hence, these models are not expected to show an early dip at a few days past explosion as is observed in SN 1999ex. The second and more favored model for SNe Ib/c consists of core collapse of massive stars (M_{ZAMS}>8 $M_\odot$) which lose their outer H envelope before explosion. Within the core collapse models, there are two basic types of progenitor systems: 1) a massive (M_{ZAMS}>35 $M_{\odot}$) star which undergoes strong stellar winds and becomes a Wolf-Rayet star at the time of explosion [25], and 2) an exchanging binary system [21,18,12] for less massive stars. The resulting SNe have lightcurves containing an initial spike followed by a dip. Since the initial radii of these progenitors are ~100 times greater than that of white dwarfs, the dip occurs several days after explosion [24,21,25], very much like SN 1999ex.

Although a detailed modeling of SN 1999ex is beyond the scope of this paper, our fortuitous observations lend support to the idea that SNe Ib/c are due to core collapse of massive progenitors rather than thermonuclear disruption of white dwarfs.

M.H. acknowledges support provided by NASA through Hubble Fellowship grant HST-HF-01139.01-A awarded by the Space Telescope Science Institute.

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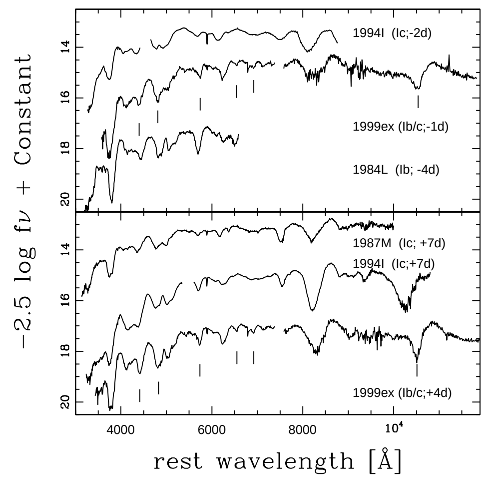

Fig. 1. Comparison of spectra of the Type Ib/c SN 1999ex with the prototype of the Ib class SN 1984L [9], and the Type Ic SNe 1994I [5] and 1987M [4]. *Tick marks* indicate the He I lines in the SN 1999ex spectra. The strengths of the helium lines gradually increase from the Type Ic to the Ib SN, and SN 1999ex provides a link between these two subclasses. Time (in days) since B maximum is indicated for each spectrum

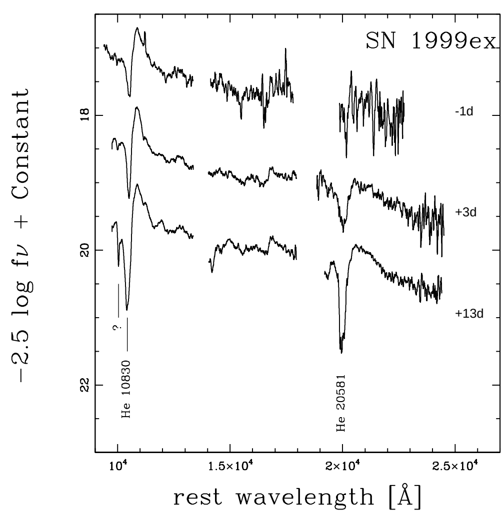

Fig. 2. IR spectroscopic evolution of SN 1999ex. The two most prominent features are attributed to He I. Time (in days) since B maximum is indicated for each spectrum

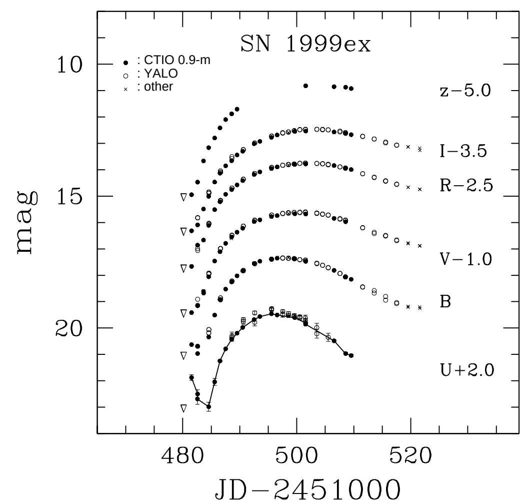

Fig. 3. *UBVRIz* lightcurves of SN 1999ex measured with the YALO (*open points*) and CTIO 0.91-m telescopes (*closed points*). Upper limits derived from images taken on JD 2,451,480.5 are also included (*open triangles*). The *solid line* through the U data is drawn to help the eye to see the initial upturn

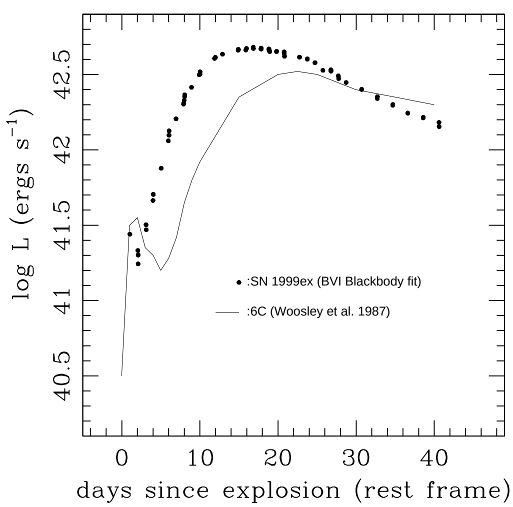

Fig. 4. Bolometric lightcurve of SN 1999ex derived from blackbody fits to the BVI magnitudes, assuming $E(B-V)_{host}$=0.28 and a distance of 51.2 Mpc (*closed circles*). The *solid line* is the 6C hydrogenless core bounce SN model of Woosley et al. [24]